Space Exploration: Oh, the Materials You'll Need!

Sylvia M. Johnson
NASA Ames Research Center

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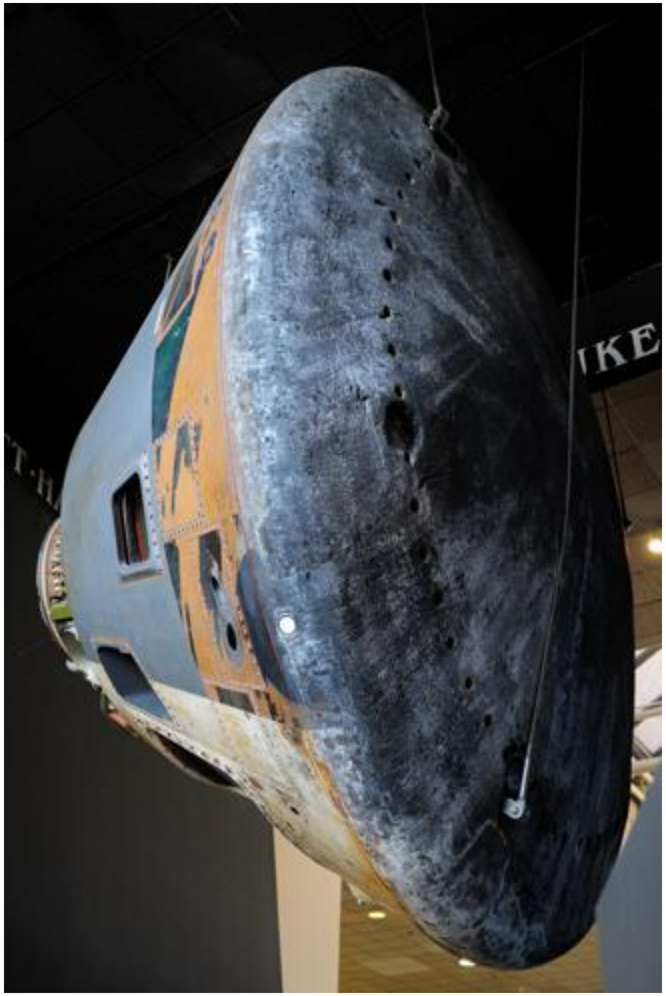
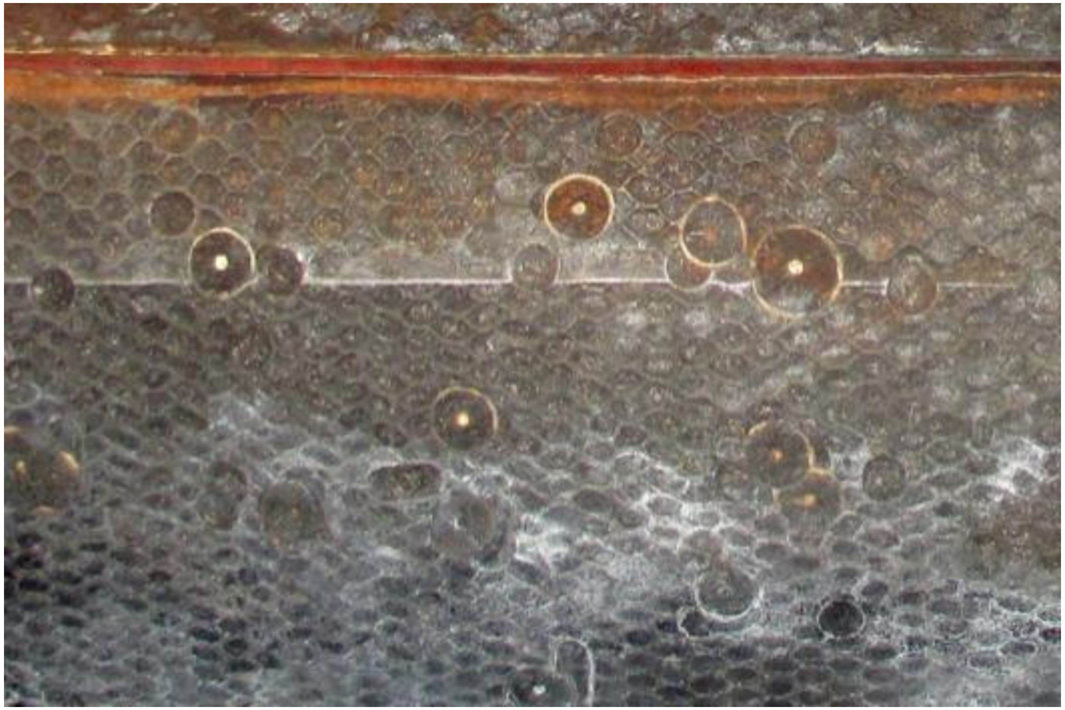
Apollo Heatshield: After Entry!





Material: AVCOAT

Space is tough on materials!

Materials in Space

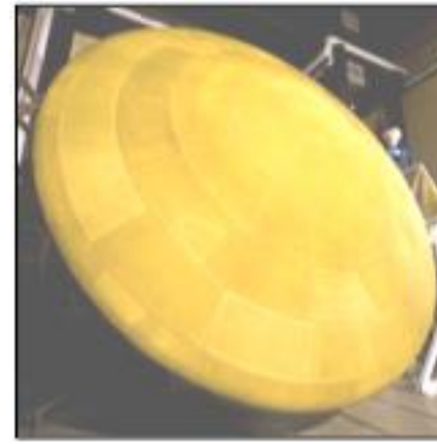
- Need to make everything out of something!
  - Understanding the systems,
  - Understand the environment
  - Function and performance in the system rule
- Any use of a new material has to show a clear advantage in performance and in risk strategy

Space Exploration

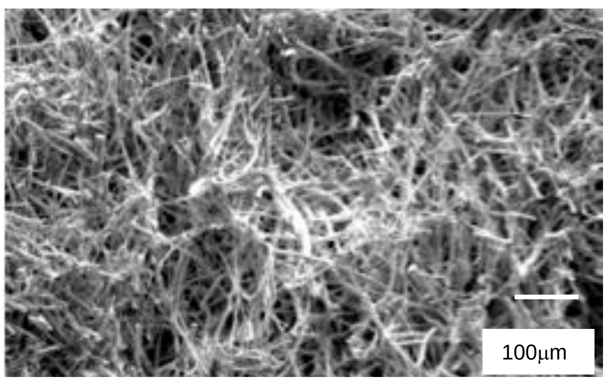
The places you'll go

The environments you'll see

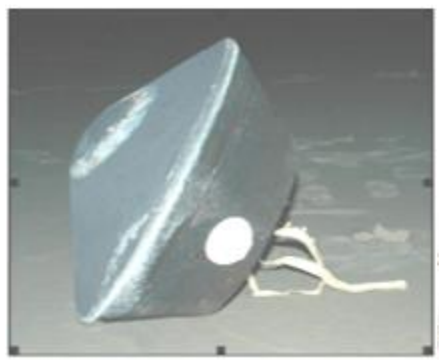
The materials challenges you'll face



MSL Heat Shield (4.5m diameter)



"Space Shuttle Tile"



Stardust sample return capsule post flight with PICA as the forebody TPS. (0.8m diameter)

Orion EFT1, post flight
http://www.nasa.gov/exploration/systems/orion/gallery/index.html?id=341169

Apologies to Dr Seuss

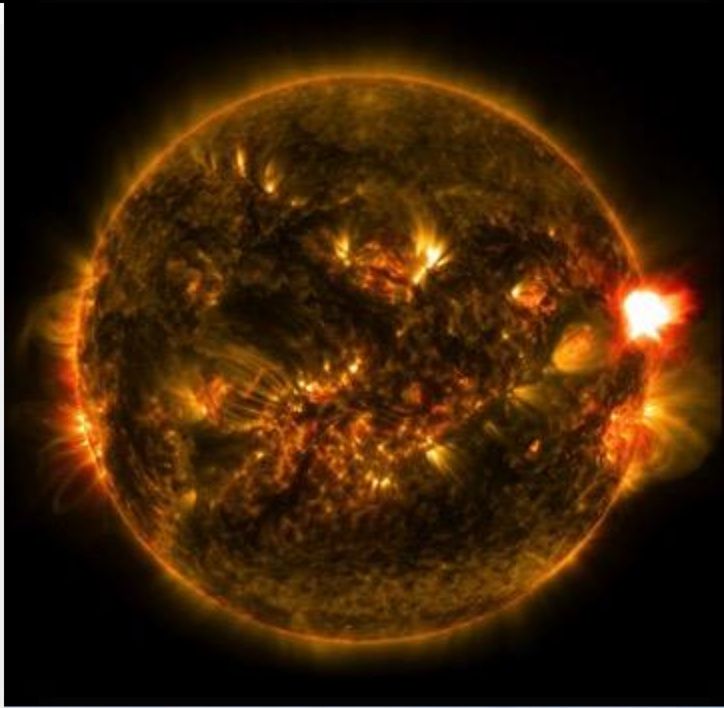
Non-crewed Exploration of Solar System

Human Exploration on Mars

Where are we going?

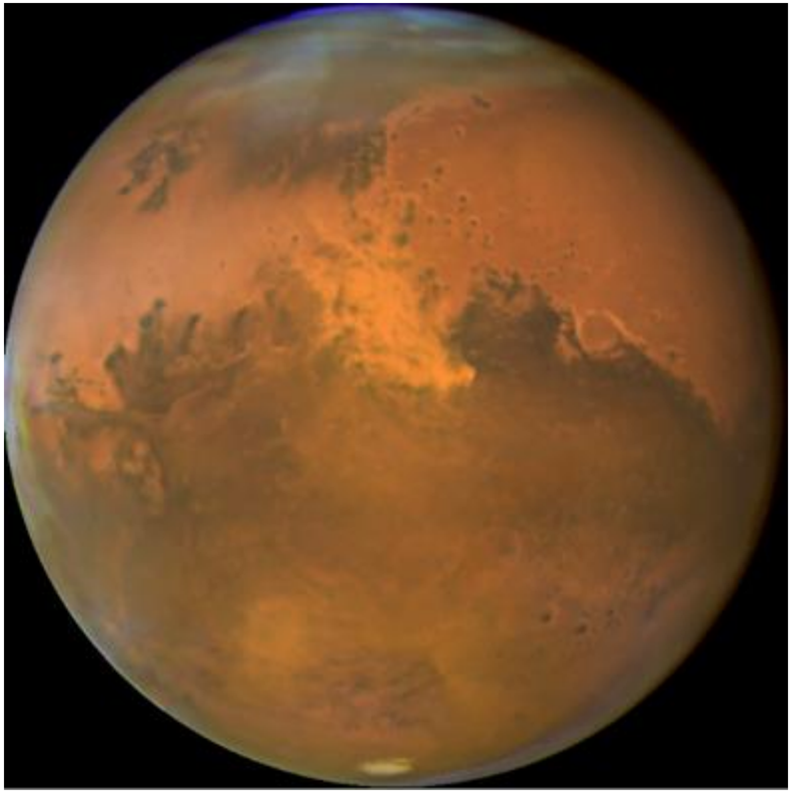
Hazards of Space Travel …and Habitation

- Time scale: Structures may be in corrosive/high UV environment for many years before use
- Solar radiation—bad for humans, bad for electronics, bad for structures
- Cosmic radiation-very bad for humans, for electronics and structures
- Micrometeroids
- Gravity: too much or too little
- Atmosphere/environment: lack thereof, or toxic species
- Lack of life support: O_2, food, water, power
- Atmospheric entry/reentry: significant structural and thermal effects on vehicles



Humans to Mars

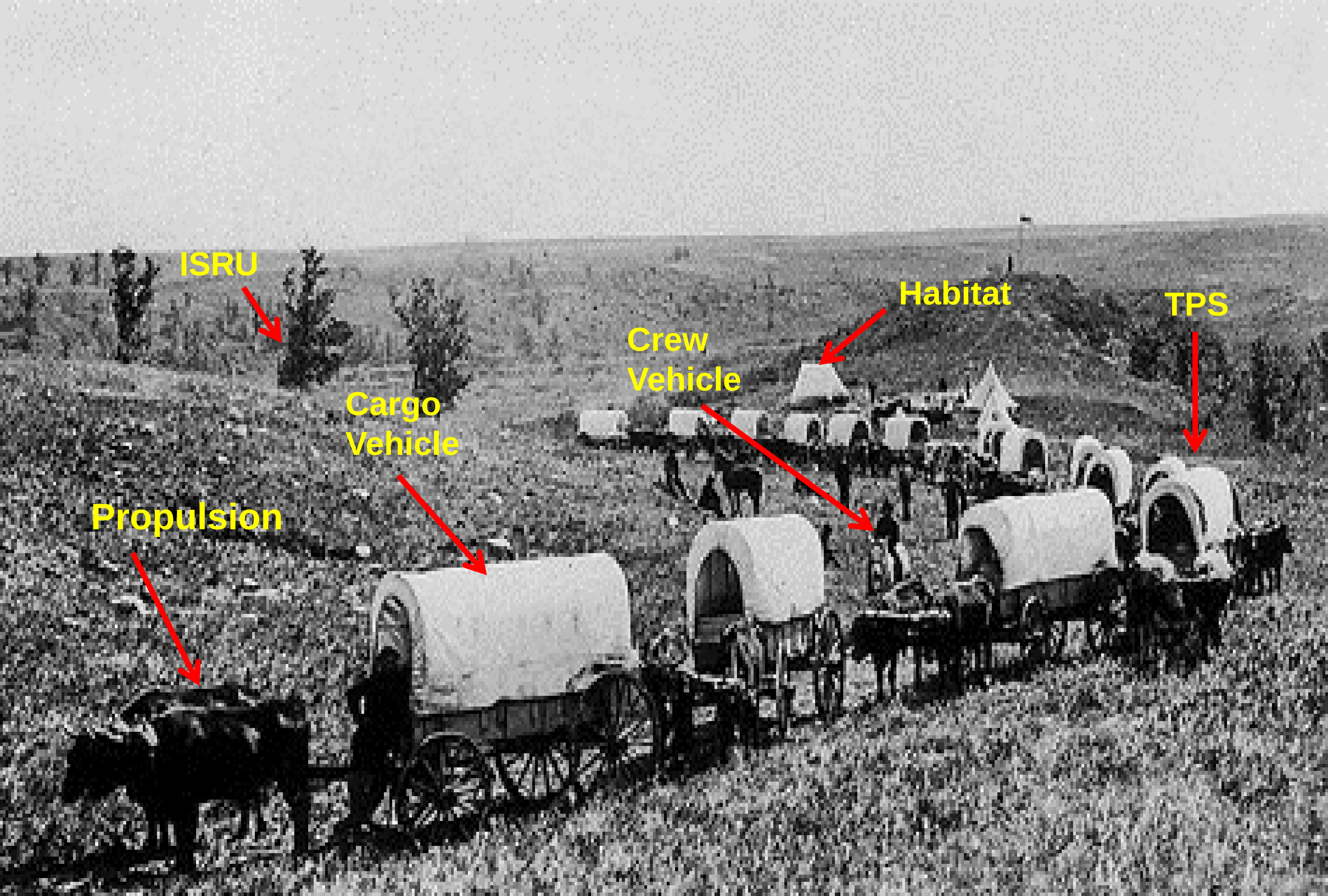
- People need a lot of equipment
- Life support
  - Habitats
  - Food
- Need equipment in place before they arrive
- May want to come home…
- Very expensive, high tech, safe expedition

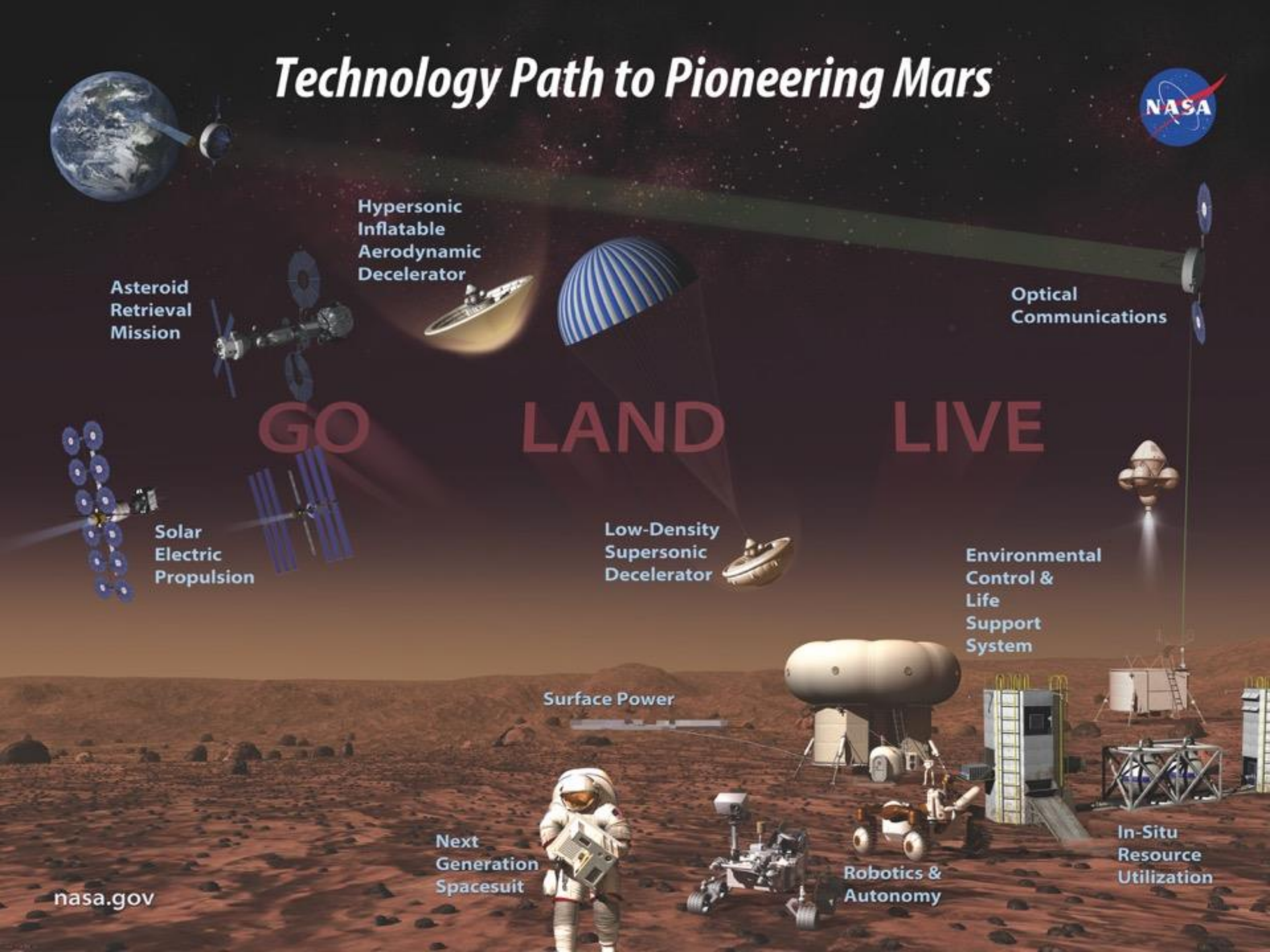


Mars in a sandstorm (2005)

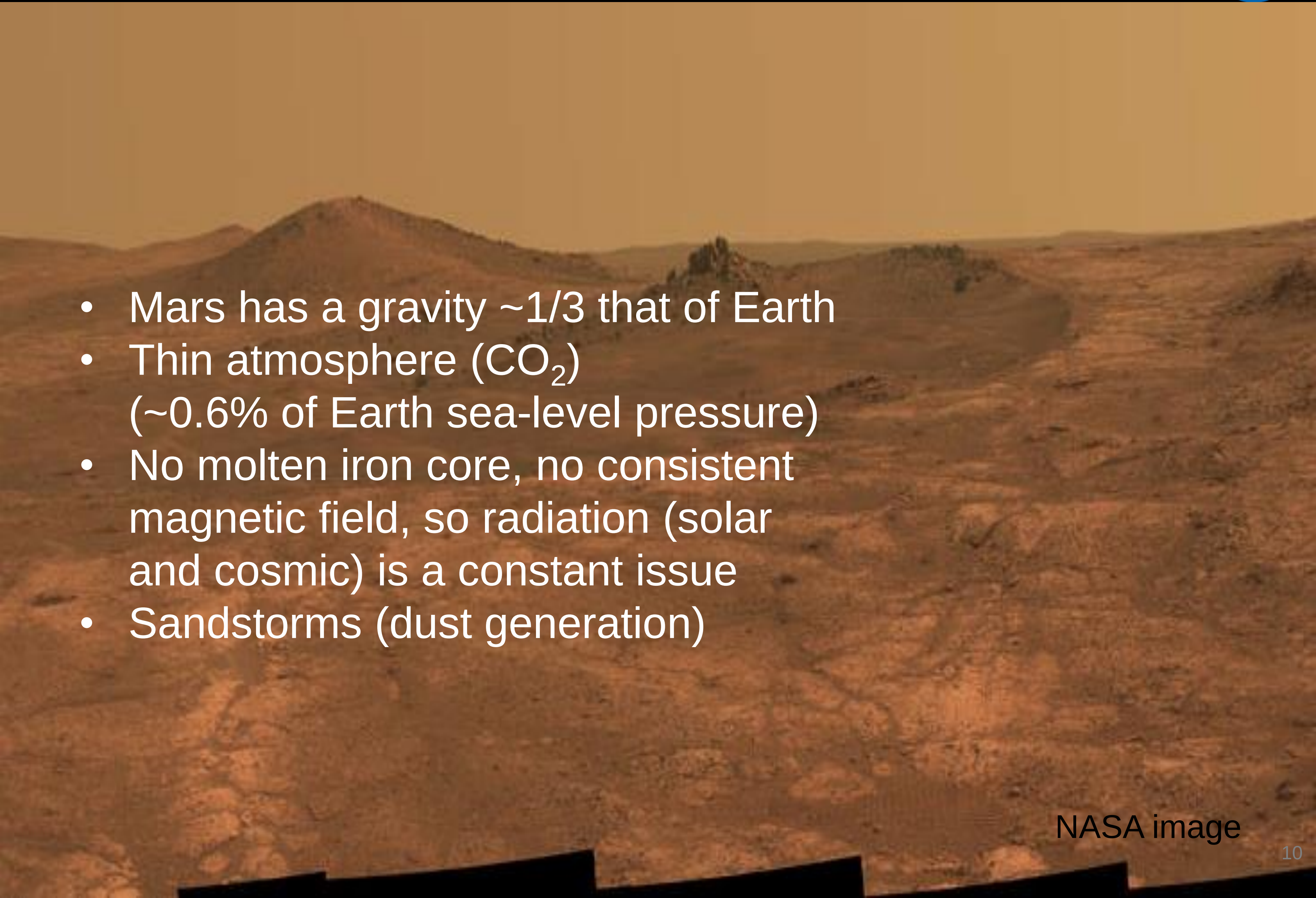
NASA: Hubble Telescope

Pioneering on Earth




Technology Path to Pioneering Mars
NASA
Hypersonic Inflatable Aerodynamic Decelerator
Asteroid Retrieval Mission
Optical Communications
GO
LAND
LIVE
Solar Electric Propulsion
Low-Density Supersonic Decelerator
Environmental Control & Life Support System
Surface Power
Next Generation Spacesuit
Robotics & Autonomy
In-Situ Resource Utilization
nasa.gov

Martian Landscape



- Mars has a gravity ~1/3 that of Earth
- Thin atmosphere (CO_2)
  (~0.6% of Earth sea-level pressure)
- No molten iron core, no consistent magnetic field, so radiation (solar and cosmic) is a constant issue
- Sandstorms (dust generation)

NASA image

System Challenges and Materials Needs

- **System Challenges**
  - **Mass reduction**
  - **Radiation protection**
  - **Reliability**

- **Materials Development Needs**
  - Lightweight structural materials
  - Computationally designed materials
  - Flexible material systems
  - Materials for extreme environments
  - Special materials

Affordability: Key to extent and timing

NASA Technology Roadmaps 2015

- http://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_12_materials_structures_final.pdf

Lightweight Structural Materials --Mass and Volume Matter!

- Emphasis
  - Reduce mass of structures that leave Earth/ enter atmosphere
  - Increase useful payload
  - Lower launch cost
  - Reduce fuel needed for return
    - ~300lbs of fuel to move 1lb from Earth to Mars and back
  - Provide more benign entry conditions
- Materials: Multifunctional structural with
  - Radiation resistance
  - Thermal protection
  - Sensors
  - Repair functions (self healing)
- Composite materials, especially polymer matrix composites

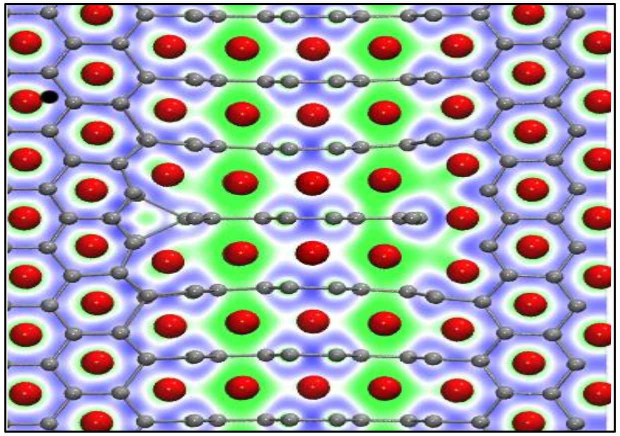
5.5m Composite Tank (MSFC)

Composite tank: saves 33% of weight and ~25% of cost

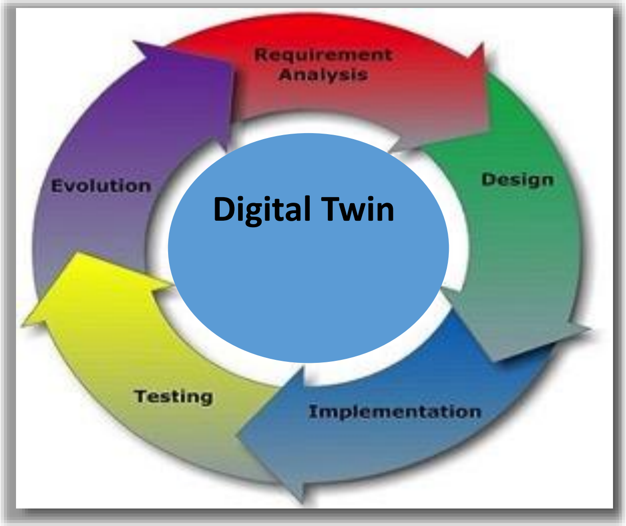
Computationally Designed Materials

Decrease development time, operational costs, improve safety

- **Emphasis**
  - Predict lifetimes—reduce testing and shorten mission insertion times
  - Design: improve/tailor properties
  - Processing: robust, reduce experiment
- Materials Design: Extension to Systems: "Virtual Digital Twin"
  - Simulation capability to manage system from concept through flight
  - Evaluate the effects of actual flight parameters



Computational model of ZrB_2 UHTC atomic structure

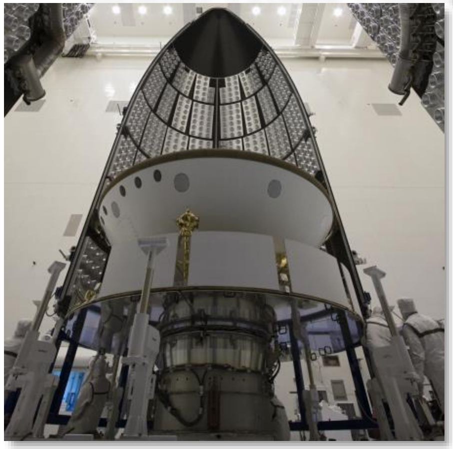


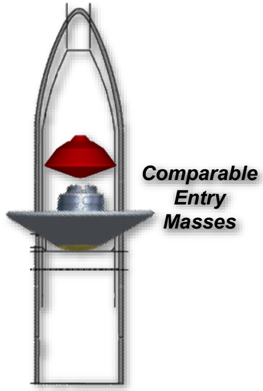
Flexible Materials

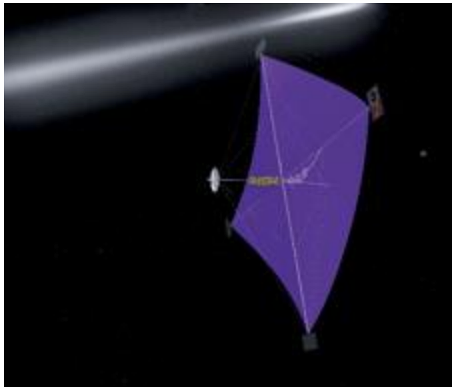
- **Emphasis:**
  - Minimize launch volume and mass and maximize use volume
- **Materials:**
  - Flexible materials for structures, (habitats), aeroshells, solar power
    - Deployed or inflated: mechanisms
    - Morphing materials: power requirements
  - Reliable life support structures : multifunctional materials.
  - Heat shields
    - Expandable aeroshells for landing large masses on Mars
- Example: Solar sails: use momentum of photons for propulsion
    - Very large, very low areal density, efficient
    - Deployment issues/stresses increase with size
    - Multilayer material
    - Goal is <2um thickness, 90,000m^2

Courtesy Inspiration Mars

Launch Vehicle Fairing Constraints







Solar sail: 0.5 km diameter

http://www.nasa.gov/centers/marshall/images/content/152149main_9906265_1140x900.jpg

Materials For Extreme Environments

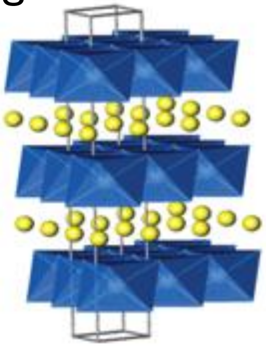
- **Emphasis**
  - Protect against extremes of temperature, pressure, corrosion, radiation and combined environments
    - Space operations
    - Planetary operations
    - Heat shields
    - Propulsion
  - Protection of electronics and people from radiation and combined environments is especially challenging
- **Materials:**
  - Ceramic matrix composites
  - Ultrahigh temperature ceramics
  - Advanced alloys
  - Coatings
  - Insulators
  - Radiation-hardened electronics
- **Example: Cryogenic insulation for fuel tanks**
  - Currently storage time is ~12 hours
  - Need: high thermal resistivity/low density
  - Enable long term storage and protection from space environments.

http://www.nasa.gov/sites/default/files/2014-12-11-rs-25chilltest.jpg

Special Materials

- **Emphasis**
  - Space suits for improved dexterity/lower weight
  - Optically transparent windows for habitats and instruments
  - Power generation:
    - Long life,
    - High efficiency
    - Radiation hardened
  - Energy storage
    - Low mass materials,
    - Reliable over long term in extreme environments and temperatures
    - Multifunctional batteries
- Goals:
  - Energy density: > 400Wh/kg
  - Power density: >100W/kg

Solar array (ESA/NASA)



Beyond Li ion batteries

http://www.nasa.gov/sites/default/files/thumbnails/image/16938569907_90b5c8a831_o.jpg

Thermal Protection Systems

- Protect vehicle structure and contents (people and things) from the heat of entry through an atmosphere
- Rely on material's response to environment
- Response depends on
  - Material properties
  - Configuration of the system
  - Specific conditions (heat flux, pressure, flow)
- Physical Forms: rigid, conformable, flexible

One size does not fit all!

Different TPS for different vehicles, location on vehicles, and mission conditions

Goal of all TPS is reliable and efficient performance

Specifically addresses challenges of mass reduction and reliability

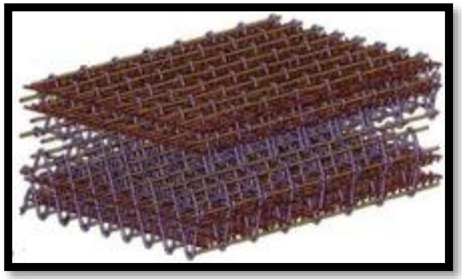
Physical Forms of TPS

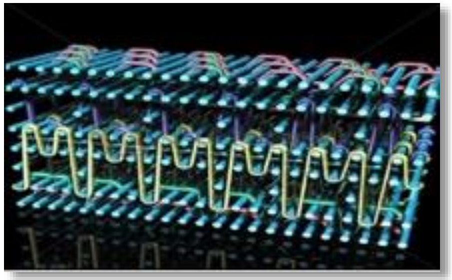
- Rigid – fabricated in a rigid form and usually applied in a tiled configuration to a rigid substructure
- Conformable – fabricated in a flexible form and shaped to a rigid substructure; final form may be rigid or compliant
- Flexible – fabricated and used in a flexible form, where flexibility is an essential component of the heatshield, e.g., deployable systems, stowable systems
- Woven – can be any of the above

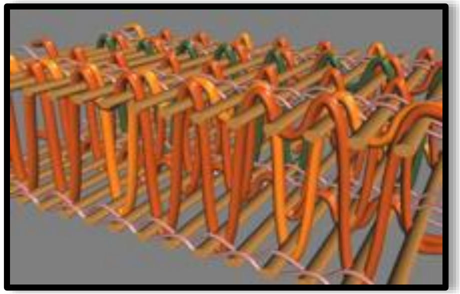
3D Woven TPS

An approach to the design and manufacturing of* ablative *TPS by the combination of weaving precise placement of fibers in an optimized 3D woven manner and then resin transfer molding when needed

- Design TPS for a specific mission
- Tailor material composition by weaving together different types of fibers and by exact placement using computer controlled, automated, 3-D weaving technology
- One-step process for making a mid-density dry woven TPS
- Ability to infiltrate woven preforms with polymeric resins for highest density TPS to meet more demanding thermal requirements



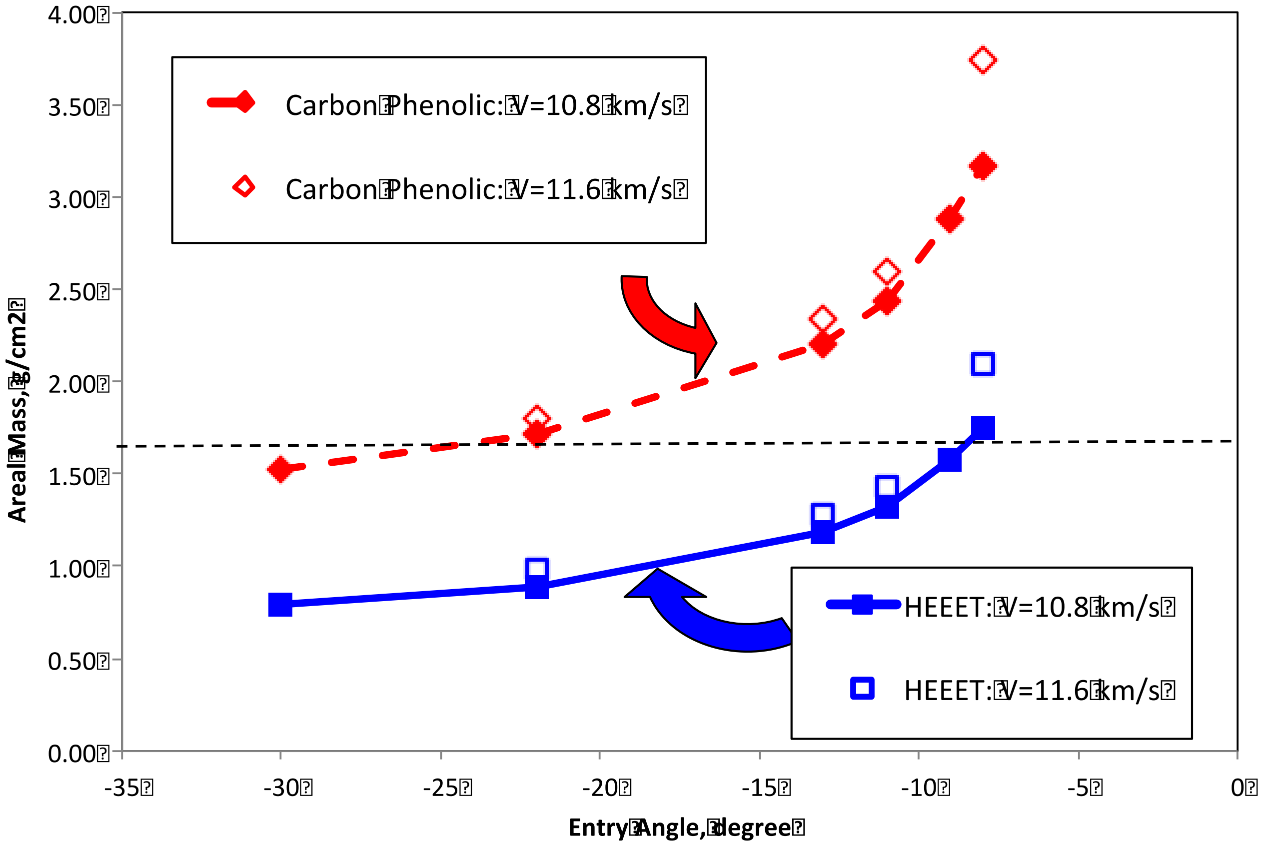


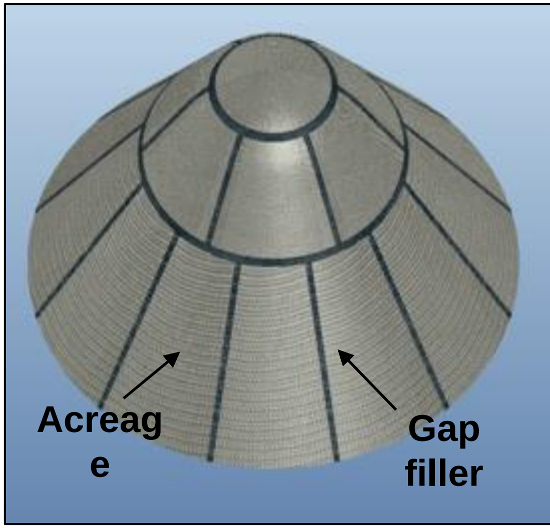


Blended Yarn

Resin infused

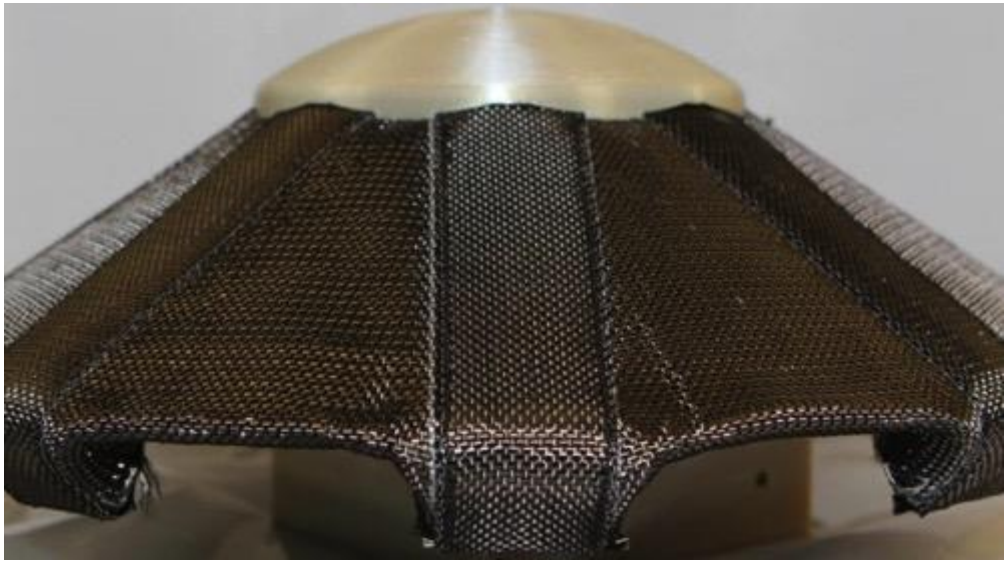
Potential Mass Savings!





- Improved mass efficiency of woven TPS material for Venus entry
  - More mass for instrumentation
  - Lower G loads

Deployable Heat Shield Concept



Test model of deployable system

TPS:

- 6 layers of carbon fiber weave (3D weave)
- Has to withstand aerodynamic and aerothermal loads.
- Medium Heat Rate Capability (250 W/cm^2)

Deployment system

Current concepts for Venus exploration

Potential for expansion to Mars entry (~16m diameter)

Large sizes will place significant demands on structure and mechanisms

Challenges for Systems in Space/Other Planets

- Must work right first/only time
  - Loss of crew/mission
  - Public relations/public money
- Environment not the same as Earth/unknown
  - Gravity, radiation, vacuum, temperature extremes, atomic oxygen, corrosion, erosion
  - Entry through atmospheres can be very challenging
- Limited or impossible testing
  - In real environment
  - Long duration
  - Whole system
  - Usually don't get flown systems back for inspection
- Mass constraints—cannot over-engineer/safety margins
- Cost

- All mean that the use new materials is met with skepticism……

So what should a materials scientist know and do?

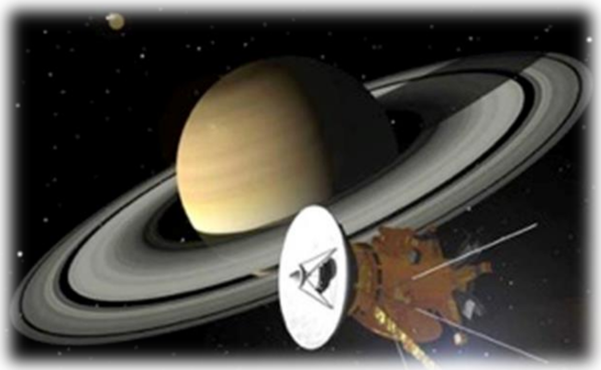
- Be knowledgeable about materials and behavior
- Think about materials behavior in extreme environments
  - How to extrapolate past the limits of testing?
- Understand the role of materials in context of the rest of the system
- Communicate with other engineers…and understand their constraints
- Champion new materials…
  - System understanding
  - Clear articulation of material's benefits…and potential downfalls.

Concluding Remarks

- Space exploration is exciting but not easy!
- Many systems require new technology
- Challenges are always
  - Mass reduction
  - Radiation protection
  - Reliability
- Affordability is also key to success

Materials innovations are key to success of critical integrated systems

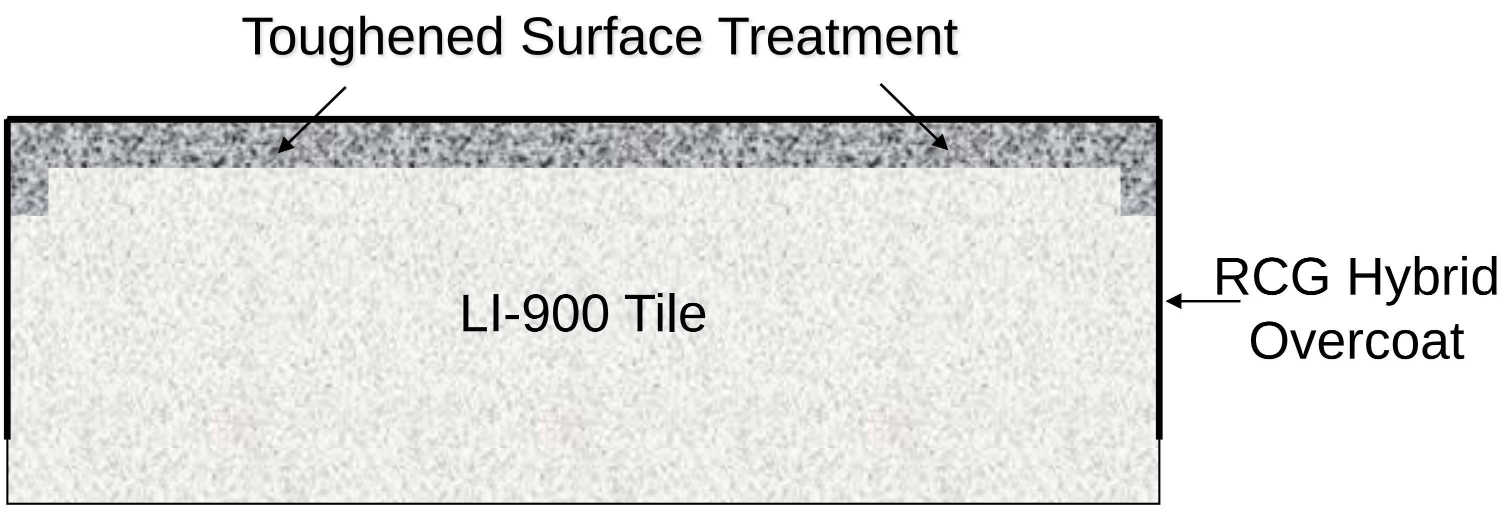
Being successful requires materials scientists and engineers with deep and broad skills



National Aeronautics and
Space Administration

Ames Research Center
Entry Systems and Technology Division

Optimized LI-900/TUFI



This system reduces the weight of TUFI/LI-900 to an acceptable level by limiting the area where the surface treatment is applied while retaining the improved damage resistance of the TUFI system.

Outline

- Introduction to TPS
- Reusable TPS
  - Shuttle materials
  - Current reusable material
- UHTCs
- Ablative TPS
  - Recent materials
  - Materials selection
  - Orion TPS
- Challenges for the future

  New materials/concepts

Entry Heating Parameters

- Reentry heating : 2 primary sources
  - **<u>Convective heating</u>** from both the **flow of hot gas** past the surface of the vehicle and catalytic chemical **recombination reactions** at the surface
  - **<u>Radiation heating</u>** from the **energetic shock layer** in front of the vehicle
- Heating depends on reentry speed (V), vehicle effective radius (R), and atmospheric density (ρ)

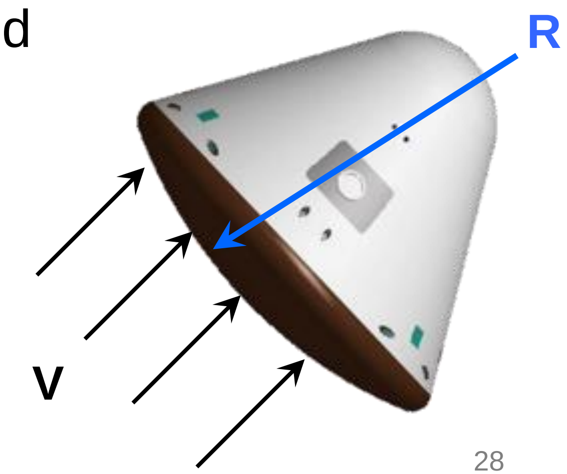
$$\dot{q}_{conv} \propto V^3 \left(\frac{\rho}{R}\right)^{0.5}$$

Convective Heating

$$\dot{q}_{rad} \propto V^8 \rho^{1.2} R^{0.5}$$

Shock Radiation Heating

- As reentry speed increases, both convective and radiation heating increase
  - Radiation heating dominates at high speeds
- As vehicle radius increases, convective heating decreases, but radiation heating increases

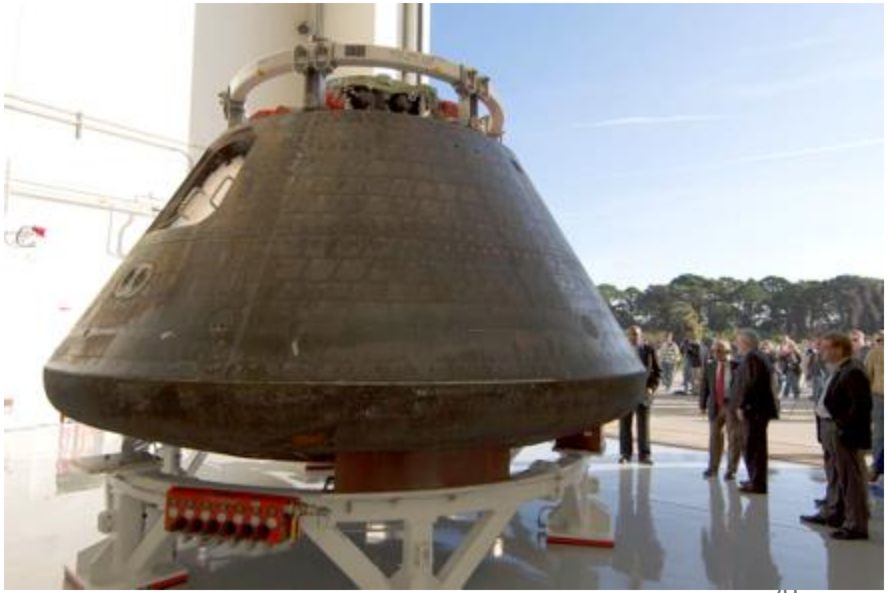


TPS Selection

- Entry into outer planets/ Venus
  - Large aeroshells for deceleration
- Entry into Mars
  - Sky crane approach of MSL/Curiosity not feasible for loads>1.5mt to Mars
  - Balloons / parachutes not very effective
  - Need large aeroshell
- High speed entry into Earth's atmosphere
  - Direct trip/ entry: entry speed> 13.5km/s
  - Orion vehicle: need more capable TPS
  - Inspiration Mars proposed very small reentry vehicle: lower heat flux, current TPS
- Scenarios have differing degrees of risk to humans—length of time in space, entry speeds, g forces, hazard of changing vehicles

Planet Mission Studies	Peak Heat Flux Range (W/cm^2)	Pressure Range (atm)	Heat Load Range (kJ/cm^2)
Venus[1]	2400 - 4900	4 - 9	11 - 12
Saturn[2]	1900 - 7700	2 - 9	80 - 272

1. Prabhu, D.K., et. al.; IEEE Aerospace Conference, Big Sky, MT, March 2-9, 2013
2. Allen, G. A. and Prabhu, D. K.; private communication



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